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Some observations on Statnamic pile testing

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Limited guidance on usage and methodology is currently available to engineers for the most common rapid load pile test, known as Statnamic. In order to improve the analysis of Statnamic testing in clay soils a full-scale instrumented auger bored pile was installed and tested in glacial lodgement till. As a result, improvements have been suggested in the test methodology and analysis. The inclusion of an accelerometer at the pile head would allow direct measurement of acceleration and verification of displacement measurements and velocity calculations. High-precision optical levelling of the pile before and after test cycles would allow multiple loading cycles to be considered cumulatively with greater confidence. The separation of the laser reference source from the test pile should be sufficient to avoid surface wave disturbance.

1. INTRODUCTION

The rapid load pile test known as the Statnamic test is seeing greater use worldwide. During Statnamic testing, fuel burns rapidly in a combustion chamber mounted on the pile. The controlled venting of the gas and subsequent pressure accelerates a reaction mass, resulting in loading of the pile for approximately 100 ms. Derivation of the equivalent static pile behaviour from the Statnamic test¹ requires accurate determination of the variation of load, velocity and acceleration with time, the last of which is typically derived by differentiating the velocity with respect to time.

Limited guidance is currently available to practitioners to allow informed use of the technology. Where guidelines have been produced, they are based upon limited experience in the United States² and Japan.³ Guidance on deriving equivalent static pile behaviour from Statnamic tests has, for example, been produced by the Florida Department of Transportation in the United States.⁴ This guidance, however, is specific to analysis of piles installed in soils other than clay, and does not cover Statnamic operating procedures and equipment.

In order to gain a better understanding and aid analysis of rapid load testing in clay soils, rapid load and static tests were compared on a full-scale instrumented auger bored pile in glacial lodgement till near Grimsby in the United Kingdom.¹ Aspects of the test procedure have been identified for consideration when undertaking Statnamic testing, and improvements suggested to the Statnamic device and testing procedures.

2. FIELD PILE STUDY

The Grimsby research site was located near Waltham, Grimsby, UK, and comprised matrix dominant glacial lodgement till,⁵ underlain by chalk bedrock at 28 mbgl.¹

2.1. Pile description and instrumentation

The instrumented test pile was a 600 mm nominal diameter auger bored cast in situ pile installed to 12.07 mbgl.¹ After excavation, a steel friction-reducing casing of 610 mm diameter was advanced to 1.8 mbgl with 480 mm left above ground. The reinforcement consisted of six vertical 12 m long T16 bars with a single T12 helical at 300 mm vertical centres.

Pile instrumentation consisted of 15 gauged T12 reinforcing bars, three at each of five different levels, tied to the horizontal reinforcement. The sister bars incorporated bonded foil strain gauges rather than the more commonly employed vibrating-wire type, which, though durable, are unsuitable for high-frequency loading.⁶ Two piezoelectric ceramic shear accelerometers were sealed in waterproof protective stainless steel housings and wired to the pile reinforcement at two levels. The rated frequency response for these accelerometers was from 3 Hz to 7 kHz. This range corresponds to a $\pm 5\%$ variation in transducer output (usable range) at varying frequencies referenced to its output at 159 Hz (1000 rad/s).

2.2. The Statnamic device

The 3 MN Statnamic rig with hydraulic catch mechanism is shown in Fig. 1. A steel plate was first fixed to the pile head using an epoxy-based adhesive to create a platform for the Statnamic piston and load cell. The outer frame of the device was located centrally over the pile, the piston was lowered onto the pile and the 18 t reaction mass lowered into place within the frame. A set of three hydraulic followers was used to lower the mass into position. These same followers are driven upwards by hydraulic accumulators during the test to catch the reaction mass on its return.

The pile load was measured by a load cell in the piston. Pile displacement was measured by a photovoltaic sensor in the piston excited by a laser reference beam mounted some distance from the pile. The laser source is typically placed between 15 and 30 m from the photovoltaic cell, with 10 m and 15 m variously specified as minima.^{2,3}

Load and displacement signals were transferred by cables via a



Fig. 1. 3 MN Statnamic device with hydraulic catch mechanism. The laser reference source can be seen in the foreground

data logger to a laptop computer. Data logging at 1 kHz was triggered by pressing a trigger, which also ignited the fuel in the piston.

3. PILE TESTING

The Statnamic pile tests were carried out sequentially over two days with target loads of 1000, 1500, 2000, 2500 and 3000 kN. The target loads were approximate, and the actual loads measured at the pile head were generally higher during testing. The Statnamic tests were followed 22 days later by a constant rate of penetration (CRP) test and 4 days after that by a maintained load test (MLT).¹ Both the MLT and the CRP test were undertaken according to the ICE guidance,⁷ with the CRP test being undertaken at 0.01 mm/s.

3.1. Pile velocity and acceleration

The load–time and settlement–time histories for a 3000 kN Statnamic pulse are shown in Fig. 2. The velocity and acceleration shown in Figs 2(b) and 2(c) were obtained by differentiating the settlement–time data.¹ The process of differentiation tends to amplify signal noise, and it is therefore necessary to use an adjacent averaging procedure to smooth the data prior to differentiation. The pile velocities calculated from settlement–time data are compared in Figs 3(a) and 3(b) with those calculated from accelerations measured by an accelerometer embedded in the pile. The velocity calculated from settlement–time data shows significant calculation-induced oscillations (Fig. 3(a)), whereas the velocity back-

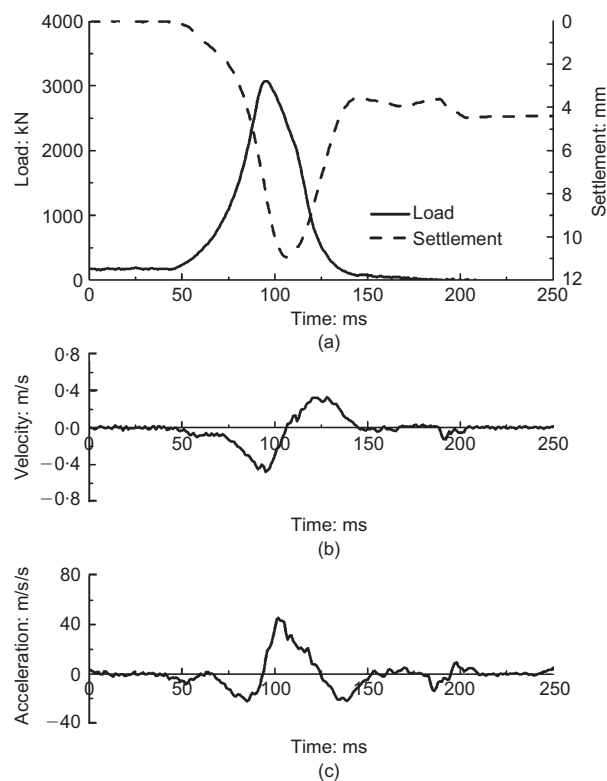


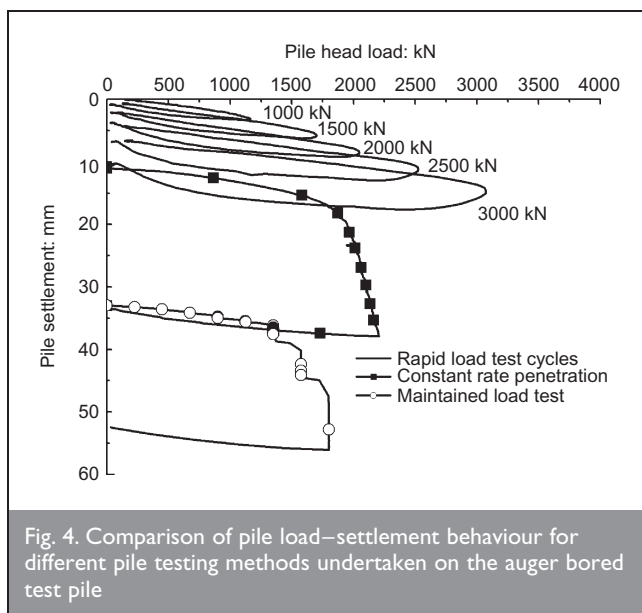
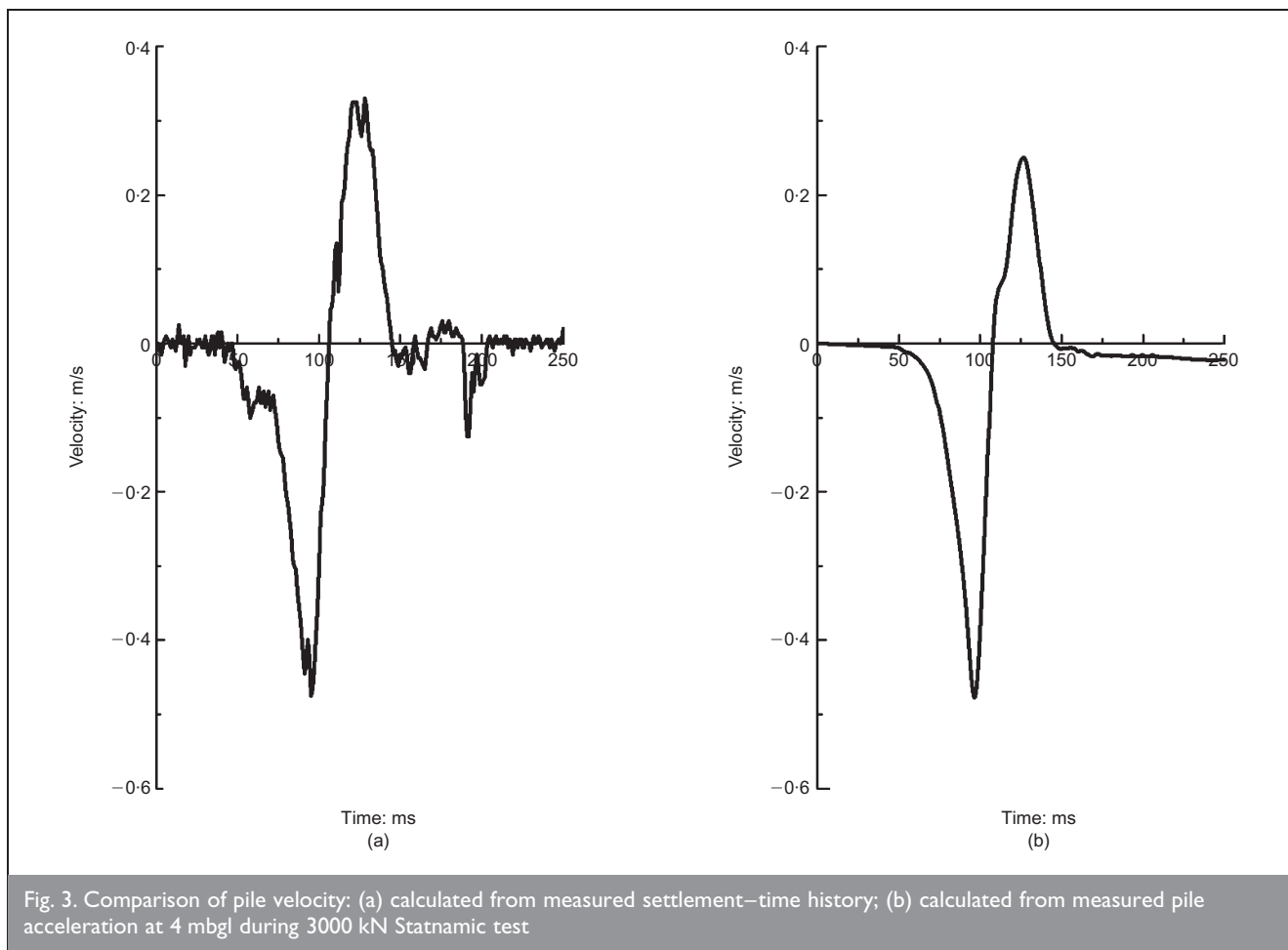
Fig. 2. Measured and calculated results from a 3000 kN Statnamic load cycle: (a) Statnamic load and pile settlement; (b) calculated pile velocity; (c) calculated pile acceleration

calculated from the measured acceleration is far smoother (Fig. 3(b)). This is because the numerical integration process is inherently more stable than differentiation. Similarly, calculation of the pile's acceleration leads to a reduction in the peak accelerations, an increase in calculation-induced noise, and a loss of some of the acceleration peaks. This problem was exaggerated by the relatively low logging rate adopted for the Statnamic tests coupled with the need to smooth the signal. The draft Japanese guidance³ suggests rates of >1 kHz, whereas the draft US guidance² suggests >4 kHz.

3.2. Load measurement and pile stresses

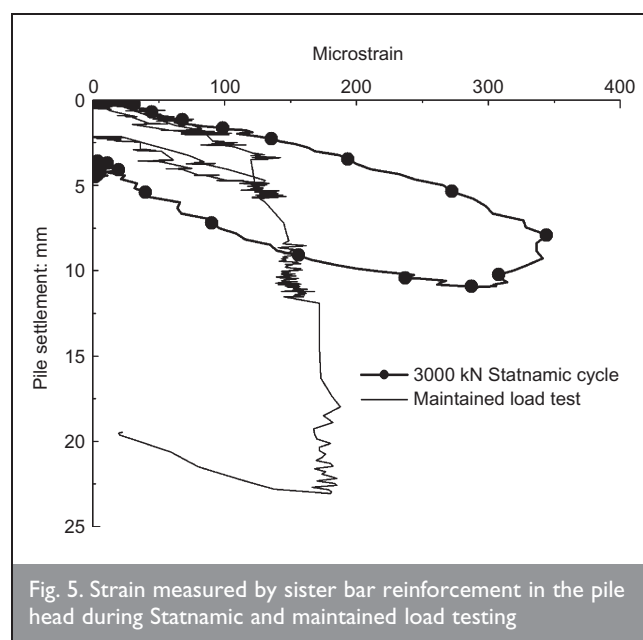
It can be seen that the loads measured during rapid load testing do not start at zero. This is because, prior to testing, the 18 t reaction mass is lowered onto the pile. The response of the pile is not normally monitored during this operation. This would seem to be a missed opportunity, as recording of the load–settlement behaviour at this stage may give significant insight into the small-strain static soil–pile stiffness⁸.

Maximum settlements during the CRP and MLT tests were 26.78 mm and 23.05 mm respectively (Fig. 4). In comparison, the 3000 kN Statnamic load cycle achieved a maximum settlement of only 10.96 mm despite having a maximum load 40% higher than that in the CRP test. Maximum Statnamic settlement was achieved at 2456 kN. Permanent settlements at the end of the CRP and MLT tests were 22.22 mm and 19.46 mm respectively. This was 84% of the maximum displacement, whereas the permanent settlement during the Statnamic test was only 32% of the maximum displacement. To achieve similar pile settlements during the Statnamic testing to



those in the static tests much greater loads need to be applied for the stiff clays in this study. For glacial till the Statnamic device must be capable of applying loads at least 1.7 times greater than the estimated ultimate static pile capacity.¹ The maximum capacity of the Statnamic device used in this study was 3000 kN. Guidance on analytical methods to derive equivalent static pile resistance from Statnamic pile testing can be found elsewhere.^{1,4,8–10}

Embedded strain measurements at 555 mm below the pile head (Fig. 5) showed that for a Statnamic pile head load 1.7 times greater than for the MLT the strain was 1.8 times greater, suggesting that there was no significant enhancement of pile head stresses due to the rate of loading. However, as significantly greater pile head loads are experienced during Statnamic testing, care should be taken to select test piles that have sufficient reinforcement to withstand the resulting higher stresses.



3.3. Settlement measurement

The load–settlement measurements during the 3000 kN load pulse shown in Fig. 2(a) show a slight apparent downward pile displacement after the Statnamic loading at 180–210 ms. Results for the 2500 kN cycle in Fig. 6 show a far more pronounced post-loading fluctuation of displacement, with the pile's final displacement approaching the maximum settlement observed during loading. To investigate this, the pile settlement for the 2500 kN cycle was calculated from embedded accelerometers at 4 mbgl and 8 mbgl (Fig. 7). The results indicate that there was no significant displacement after the initial Statnamic pulse. The apparent settlements are therefore attributed to movement of the laser reference source. This is plausible, as significant ground vibrations or surface waves were felt by the authors during Statnamic testing. Similar vibrations were reported by Brown,¹⁰ who suggested that the laser reference source should be placed at such a distance from the test pile that the surface waves arrive after the Statnamic loading has occurred.

In order to investigate the influence of surface waves in the glacial till, shear wave (S-wave) velocities were obtained from seismic cone penetration tests (SCPT) (Fig. 8). Although

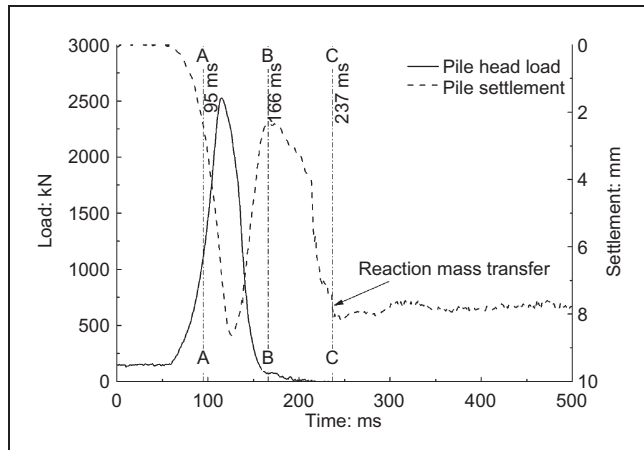


Fig. 6. Measured load and pile settlement during a 2500 kN Statnamic pulse

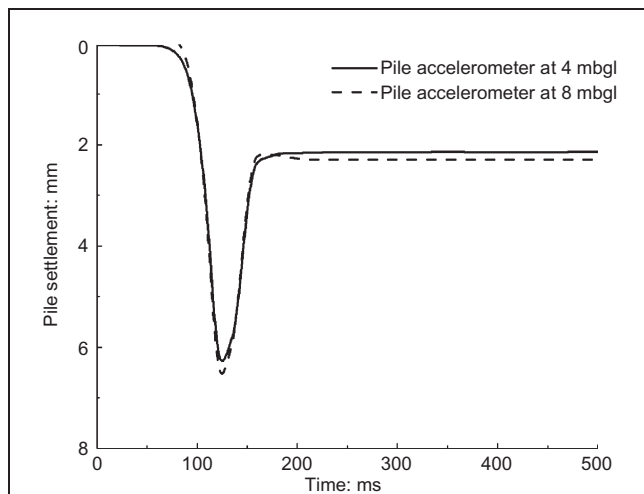


Fig. 7. Calculated pile settlement from embedded accelerometer measurements during a 2500 kN Statnamic test

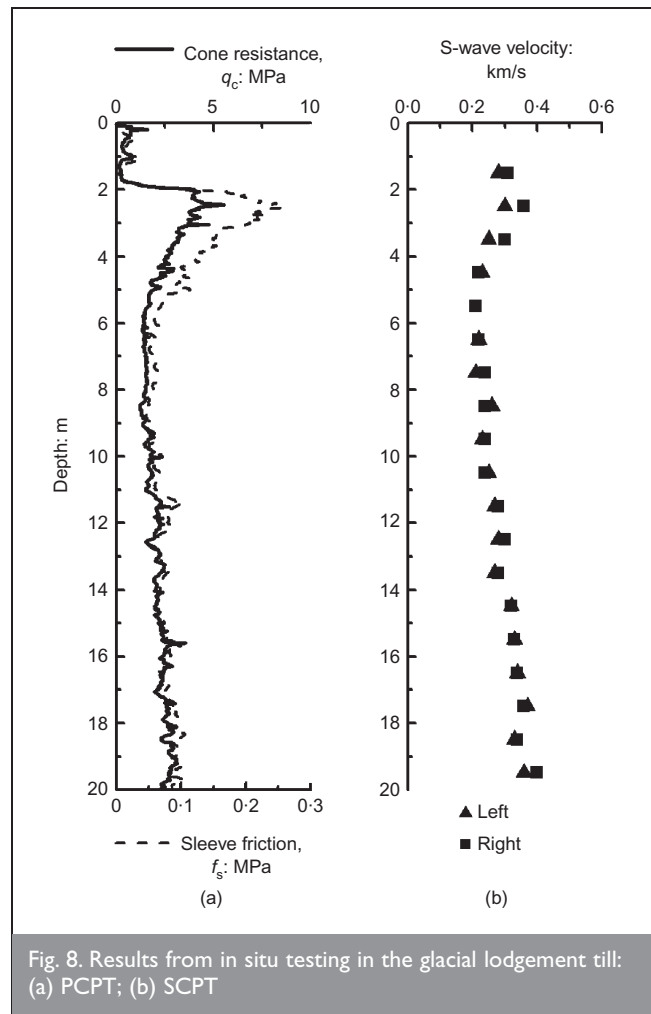


Fig. 8. Results from in situ testing in the glacial lodgement till: (a) PCPT; (b) SCPT

measurements of S-wave velocity were not undertaken in the upper 1.5 m, it is likely that the S-wave velocity would have been towards the lower end of the measured values, given the low cone resistance in the upper soil stratum (Fig. 8). If it is assumed that disturbance to the laser reference source was caused by S-wave transmission at the minimum measured velocity of 210 m/s in the upper strata, then, with a laser reference source at 15 m from the pile, the travel time to the laser would be 71 ms. In Fig. 6 the post-loading settlement is complete by point C (237 ms), 71 ms after the end of the pile loading (point B, 166 ms) where the post-event settlement measurement becomes apparent. Assuming that point B marks the initiation of disturbance of the laser, then the surface wave travelling to the laser must have commenced at point A some 71 ms earlier. This suggests that the pile did not transmit surface waves of significant amplitude until it had reached a settlement of 2.44 mm. The rapid change in settlement from 7.47 to 8.09 mm at point C is thought to be consistent with the transfer of force to the ground owing to catching of the reaction mass. This event is also identifiable in the 3000 kN test at approximately 200 ms (Fig. 2). The results show that there is potential for interference with the pile settlement measurements towards the latter stages of the Statnamic pulse. Based upon these observations, recommendations of minimum laser–pile separations are shown for varying soil types in Table 1. The recommended values were calculated based upon published S-wave velocities for different soil types with a load pulse duration of 100 ms. This suggests that the laser source should be at least 23 m (Table 1) from the test pile rather than

Soil type	Typical S-wave velocity: ^{1,11} m/s	Minimum laser–pile separation: m
Loose sand	90–155	16
Dense sand	230	23
Soft to firm clay	155	16
Stiff clay	210	21
Loose gravel	185	19
Dense gravel	230	23

Table 1. Recommendations for pile–laser source minimum separation for varying soil types

10–15 m,^{2,3} although further research is required to verify these recommendations.

It should be noted that post-loading displacement was not apparent for all of the test cycles. This is thought to be a result of varying the location of the laser reference source, which was at different times placed either directly on the ground surface or on an adjacent concrete roadway. Good practice would suggest undertaking at least one cycle of loading on a pile to check for the effects of surface waves on settlement measurement. It would also be useful to incorporate an accelerometer on either the pile or the Statnamic piston to verify the measured settlement. In addition, high-precision optical levelling of the pile before and after each cycle of loading would allow multiple loading events to be considered cumulatively with greater confidence.

4. CONCLUSIONS

The accuracy of Statnamic analyses would benefit considerably from the inclusion of an accelerometer at the pile head. This would allow direct measurement of acceleration, and provide verification of settlement measurements and velocity calculations. High-precision optical levelling of the pile before and after each loading event would allow multiple loading cycles to be considered cumulatively and allow verification of settlement measurements. Prior to testing, the separation of the laser reference source from the test pile should be selected to avoid test-induced surface wave disturbance during settlement measurement. Note that significantly greater load must be applied to a pile during rapid load testing in glacial till to produce the magnitude of permanent settlement observed during static pile tests.

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